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PLASMAS IN THE EARTH'S MAGNETOTAIL

by

L. A. Frank

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Department of Physics and Astronomy
The University of Iowa
Iowa City, Iowa 52242

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PLASMAS IN THE EARTH'S MAGNETOTAIL

L. A. Frank
Department of Physics and Astronomy
The University of Iowa
Iowa City, Iowa 52242
U.S.A.

ABSTRACT. An overview of the general characteristics of plasmas within the Earth's magnetotail and its environs is presented. Present knowledge of the plasmas within these regions as gained via in situ measurements provides the general theme, although observations of magnetic fields, energetic particles and plasma waves are included in the discussion. Primary plasma regimes in the magnetotail are the plasma sheet, its boundary layer, the magnetotail lobes, the boundary layer at the magnetopause and the distant magnetotail. Although great progress in our understanding of these regions is evident in the literature of the past several years, many of their features remain as exciting enigmas to be resolved by future observational and theoretical investigation.

1. INTRODUCTION

Since the solar wind and magnetosheath provide the boundary conditions along the outer skin, or magnetopause, of the magnetotail our first two sections summarize the gross properties of these two regions. The boundary layer at the surface of the magnetotail, or magnetopause boundary layer, is comprised primarily of antisunward flowing plasmas of solar wind origins, that have entered the magnetotail. The nature of this boundary layer at polar and equatorial latitudes is given in Section 4. The largest plasma reservoir in the magnetotail is the plasma sheet, an extensive body of plasma centered on the position of the neutral sheet where the magnetic field exhibits a dramatic reversal of direction. Discussion of the primary features of this plasma sheet and its boundary layer is provided in Section 5. High-speed ion flows, field-aligned currents and broadband electrostatic noise are found in the boundary layer of the relatively docile plasma sheet. This plasma sheet boundary layer is an important topological and energy transport region of the magnetotail. A general paucity of plasma is one of primary observational features of the magnetotail lobes. However recent sightings of ionospheric ion beams and the increasing awareness of polar cap auroras are responsible for stimulating renewed interest. The available information concerning the plasmas in these regions where large magnetic energy is stored is offered in Section 6. At great distances in the magnetotail, i.e., beyond the lunar orbit, direct measurements are only available for the occasional passage of an interplanetary spacecraft through these regions until the pioneering

survey with ISEE 3. Major results of this important investigation of the distant magnetotail and their relevance to the extensive findings inside the lunar orbit are given in the last section.

Clearly the scope of the present overview must be limited to major features of the magnetotail and its environs. The intent is to provide our colleagues in related research areas with a tutorial monologue with sufficient references to allow pursuit in detail of any of the numerous topics cited in the presentation.

2. SOLAR WIND

The solar wind is the primary source of energy for the sustenance of the magnetotail and one of the two significant sources of plasmas. The other primal source of plasmas for the magnetotail is the Earth's ionosphere. In the spirit of our presentation typical solar wind ion densities and temperatures are 1 to 10 cm^{-3} and 2×10^4 to 2×10^5 °K, respectively (Wolfe, 1972; Feldman et al., 1978). Electron temperatures are generally in the range of 6×10^4 to 3×10^5 °K (Feldman et al., 1975; Montgomery, 1972). Flow speeds at Earth's orbit are typically 200 to 600 km/sec. The solar wind exhibits large-scale plasma features such as high-speed streams associated with coronal holes and low-speed streams near interplanetary sector boundaries (Hundhausen, 1972; Burlaga, 1979). The magnetotail is naturally expected to respond to fluctuations in the solar wind (cf. Burlaga, 1975). For example, the hydrostatic pressure affects the overall geometry of the magnetotail and thus also the associated magnetic energy (cf. Coroniti and Kennel, 1972). Minor ions in the solar wind are important in determining the relative importance of the solar wind and ionospheric sources of ions throughout the magnetotail. The dominant minor ion is He^{++} (Bame et al., 1968; Bame, 1983). Other minor ions, e.g., $^3\text{He}^{++}$ and O^{6+} , are expected to increase in utility as tracers for plasma entry and motion in the magnetotail as the measurement capability increases. The magnitude of the interplanetary magnetic field is in the range of 2 to 15 nT and grossly organized into sectors of sunward and antisunward fields in an Archimedean spiral pattern as predicted by Parker (Klein and Burlaga, 1980; King, 1979; Slavin and Smith, 1983). The high degree of responsiveness of the plasma convection and magnetic topology of the magnetotail to the direction of the interplanetary fields is well established (cf. Russell and McPherron, 1973).

3. MAGNETOSHEATH

Ion densities and temperatures within the magnetosheath are in the ranges of ~ 2 to 50 cm^{-3} and 5×10^5 to 5×10^6 °K, respectively. The ion bulk flow speed is ~ 200 to 500 km/sec (Bame, 1968; Montgomery et al., 1970; Formisano et al., 1983). Electron temperatures are in the range of $\sim 10^5$ to 10^6 °K (references above; Feldman et al., 1983).

Although such measurements are available, there are no published surveys of ions within the magnetosheath along the flanks of the magnetotail. Often, in order to obtain representative plasma parameters, it is necessary to refer to such hydromagnetic treatments as that of Spreiter et al. (1966). A hot plasma component with ion energies in the range of 10 keV is also reported for the magnetosheath (Asbridge et al., 1978). The source is located either at the bow shock or within the magnetosphere, i.e., leakage through the magnetopause. Sanders (1981) finds an ion component with temperatures similar to those within the solar wind at distances $\sim 60 R_E$ downstream in the magnetosheath. The existence of such an ion distribution may indicate the direct penetration of solar wind plasmas into the downstream magnetosheath at large distances from the subsolar bow shock. A property of ion velocity distributions within the magnetosheath that is similar to those found in many regions of the magnetotail is a high-energy (speed) tail (Formisano, 1973; Peterson et al., 1979; Sanders, 1981). Such ion velocity distributions depart from a Maxwellian form within several characteristic thermal energies. When ion temperature anisotropies are observed, $T_{\perp} > T_{\parallel}$. Magnetic fields in the magnetosheath are more extensively investigated than the plasmas (Fairfield, 1976). Along the flanks of the magnetotail the magnitudes of the magnetic fields are similar to instantaneous values for the interplanetary field, and the direction of these magnetosheath magnetic fields more or less exhibits the same orientation as that of the interplanetary field. Departures from such positive correlations of interplanetary and magnetosheath magnetic fields are observed, in particular within the subsolar magnetosheath (Crooker et al., 1984).

4. PLASMA BOUNDARY LAYER INSIDE THE MAGNETOPAUSE

The magnetopause is usually identified as the position at which there is a clear transition from magnetic fields associated with the magnetosheath to those expected for a distorted geomagnetic cavity (Paschmann et al., 1978, 1979; Aubry et al., 1971). The thickness of the magnetopause is generally of the order of 5 to 10 ion gyroradii at 1 keV, or ~ 400 to 800 km (Berchem and Russell, 1982). Near the subsolar region the identification of the magnetopause is typically unambiguous in the magnetic field signature. Along the flanks of the magnetotail the magnetopause location is not as clearly resolved with the magnetic field measurements alone, and plasma observations must be utilized to identify this boundary (cf. Eastman et al., 1985). Near the subsolar magnetopause evidence of large-scale quasi-stationary reconnection is occasionally found (Paschmann et al., 1979). The importance of this mechanism for significant plasma entry into the magnetosphere is questioned by Eastman and Frank (1982) on the basis of the infrequent observations of accelerated ion bulk flows and of

inconsistent evidence for open geomagnetic fields in these regions. The recent detection of 'flux transfer events' may in fact resolve these ambiguities with the introduction of the concept of sporadic reconnection of solar wind and geomagnetic fields on a significantly smaller spatial scale over the surface of the subsolar magnetopause (Russell and Elphic, 1979; Russell, 1984). The relatively good efficiency by which magnetosheath plasmas penetrate the magnetopause is demonstrated by the existence of a thick zone of magnetosheath-like plasmas that is present behind the magnetopause locations not only at subsolar positions but along the flanks of the magnetotail at polar and equatorial latitudes. This plasma region is known as the magnetopause boundary layer. The thickness of the magnetopause boundary layer of generally antisunward flowing plasmas is $\sim 2,000$ to $10,000$ km. The mechanism for entry of these plasmas into this relatively thick region behind the magnetopause is not identified, e.g., small-scale reconnection or diffusive transport (Eastman et al., 1985). Quantitative evaluations of the plasma transport in the magnetopause boundary layer are not currently available for these various mechanisms.

The magnetopause boundary layer at polar latitudes includes the entry layer, the distant polar cusp and the plasma mantle as shown in Figure 1. The entry layer is a region of relative magnetic and plasma turbulence that is identified as the location of plasma entry into the polar magnetosphere and the source of the downstream magnetopause boundary layer (Paschmann et al., 1976). The polar cusp is associated with magnetic field lines that provide direct entry of magnetosheath

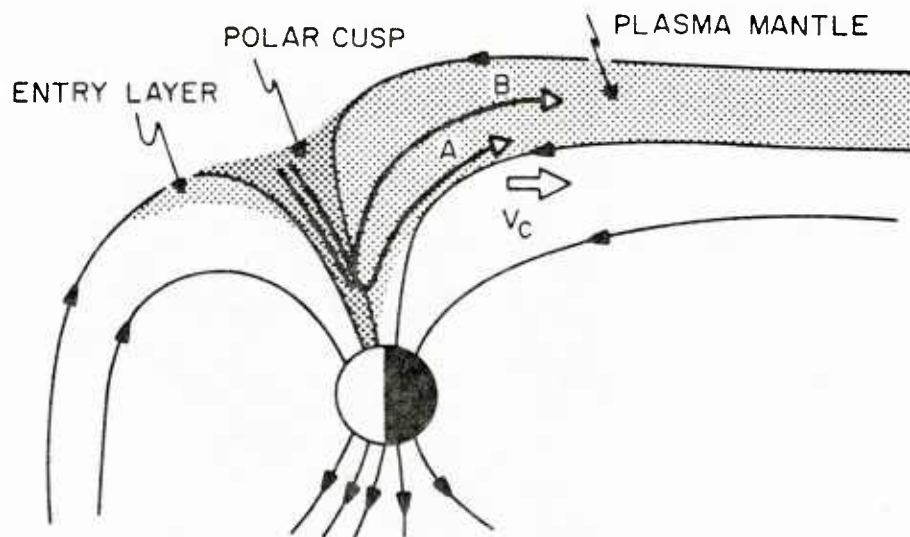


Figure 1. Plasma regions in the polar magnetosphere (noon-midnight meridional plane).

plasmas into the polar ionosphere (Frank, 1971), and the plasma region inside the downstream polar magnetopause with plasmas of direct magnetosheath origins is the plasma mantle (Rosenbauer et al., 1975). The temperatures of ions in these three regions are $\sim 5 \times 10^5$ to 8×10^6 °K and electron temperatures are $\sim 10^5$ to 10^6 °K. The range of ion temperatures appears to be equal or somewhat higher than that observed within the magnetosheath, and electron temperatures are similar. Densities are in the range of ~ 0.5 to 50 cm^{-3} . Ion bulk flow speeds in the polar magnetospheric boundary layer are typically 100 to 300 km/sec. The ion bulk velocities are approximately field-aligned in the polar cusp and plasma mantle. In the polar cusp field-aligned electron current sheets are observed. At low altitudes above the ionosphere in the polar cusp the densities of the magnetosheath plasma are generally lesser (Heikkila and Winningham, 1971). Within the plasma mantle, density and ion temperature gradients are observed such that the density and ion temperatures decrease with increasing distance from the magnetopause. At least part of these gradients can be accounted for by the velocity filter effect due to antisunward convection and penetration of plasma into the polar cusp (see Figure 1). Slower ion A will arrive at a greater distance from the magnetopause than faster ion B at a given distance downstream from the Earth. The thickness of the plasma mantle is $\sim 3,000$ to $20,000$ km. Entry of magnetosheath plasmas along the magnetopause that bounds the plasma mantle is neither demonstrated or excluded by in situ measurements. The major source of these plasmas is currently thought to be the magnetosheath via the entry layer.

Plasmas of direct magnetosheath origins are found inside the magnetopause at equatorial latitudes at all local times, i.e., in the subsolar regions and extending along the flanks of the magnetotail (Eastman et al., 1976, 1985; Paschmann et al., 1978; Skopke et al., 1981). This region is approximately 2,000 to 10,000 km in thickness near the subsolar point and appears to thicken to 5,000 to 20,000 km at distances ~ 20 to $40 R_E$ (R_E , Earth radii) downstream from the Earth. Ion densities are in the range of ~ 1 to 50 cm^{-3} with values similar to those within the magnetosheath near the magnetopause and decreasing by an order of magnitude at the earthward edge of the magnetopause boundary layer. The ion temperatures in the boundary layer are similar or greater than magnetosheath ion temperatures in the vicinity of the magnetopause and increase with increasing distance from the magnetopause. The ion temperatures in the magnetopause boundary layer at low latitudes range from $\sim 2 \times 10^6$ °K to 2×10^7 °K. The ion composition is dominantly H^+ and He^{++} , thus further establishing the direct magnetosheath origins of these plasmas (Peterson et al., 1982). Electron temperatures are usually $\sim 10^5$ to 2×10^6 °K. These magnetosheath-like plasmas coexist with hotter ion and electron plasmas of the outer magnetosphere. The ion bulk flows are generally directed antisunward and the characteristic flow speeds are in the range of 100 to 300 km/sec. These speeds are often similar to those observed in the adjacent region of the magnetosheath. The flow speed usually exhibits no or a small variation with increasing distance from the

magnetopause. When such a variation is observed, the flow speed decreases with increasing depth relative to the magnetopause position. In contrast to the field-aligned plasma flows in the magnetopause boundary layer at polar latitudes as noted previously, the ion bulk velocity at equatorial latitudes is directed at a large angle to the local magnetic field (cf. Eastman et al., 1985). The polarization electric fields associated with the ion bulk velocities observed within the boundary layer are expected to generate field-aligned currents with closure in the ionosphere. Such currents arising from field-aligned velocity distributions of electrons are observed; the corresponding current densities are $\sim 10^{-8}$ to 10^{-7} A/m². At low altitudes these field-aligned currents should correspond to the polar system, or Region 1, of field-aligned currents (Potemra, 1979; Bythrow et al., 1981). The plasma bulk velocity in the magnetopause boundary layer exhibits a component of ~ 10 km/sec in the direction perpendicular to the magnetopause (Eastman et al., 1985). The existence of such a normal flow component over a substantial fraction of the magnetopause indicates that magnetospheric plasma entry into the magnetosphere may not be restricted to subsolar positions. The observation of this large-scale plasma entry can be used to predict the increased dimensions of the magnetospheric boundary layer at the lunar orbit, $\sim 60 R_E$, downstream in the magnetotail. Such an increase in thickness to 15,000 to 30,000 km is perhaps indicated by plasma surveys at the lunar orbit (Hardy et al., 1979a). Electron angular distributions closer to the Earth at $< 20 R_E$ radial distances often indicate that the magnetic field lines threading the magnetopause boundary layer are closed, i.e., geomagnetically trapped electrons. The magnetic field is characterized by a northward direction in most of this region and by large fluctuations of spatial and/or temporal origins. Conservative estimates for the global power input into the magnetopause boundary layer are 10^{11} to 10^{12} watts, values adequate to sustain magnetospheric convection, ionospheric losses and magnetotail outflow (Eastman et al., 1985). Thus a theoretical understanding of the mechanism for formation of the magnetopause boundary layer is expected to be a substantial contribution to the development of global models of solar wind momentum and mass transport into the magnetosphere.

5. THE PLASMA SHEET AND ITS BOUNDARY LAYER

The first direct finding of the existence of an extended magnetotail in the antisunward direction from Earth is reported from magnetic field observations in these regions (Ness, 1965). This magnetotail comprises two large flux tubes with magnetic fields directed in the solar and antisolar directions in the northern and southern flux tubes, respectively. At the common midplane between these two flux tubes and generally parallel to the ecliptic plane, the magnetic field exhibits a dramatic reversal between solar and antisolar directions. This plane is referred to as the neutral sheet. Typical magnitudes of the

magnetic field in the flux tubes are ~ 20 to 50 nT at $\sim 20 R_E$ (Fairfield, 1979). A thick zone of lesser, more disordered magnetic fields at the magnetotail midplane is the signature of a sheet of plasma. Plasmas associated with the current sheet that must support this extended magnetotail are first identified by Bame and coworkers with measurements at $\sim 17 R_E$ geocentric radial distance (Bame et al., 1967; Bame, 1968). This plasma sheet extends across the midplane of the magnetotail with typical thicknesses of ~ 4 to $6 R_E$. Typical ion and electron temperature ranges are 5×10^6 to 5×10^7 °K and 2×10^6 to 2×10^7 °K, respectively, with large fluctuations during substorms. As within the magnetosheath ion temperatures are greater than electron temperatures by factors of ~ 3 to 5 . The reason for this nonequilibrium of ion and electron temperatures in the plasma sheet is believed to be associated with the primary magnetotail acceleration mechanism and remains unresolved at this time. Plasma densities within the plasma sheet are ~ 0.1 to 1 cm^{-3} . Ion bulk speeds within the plasma sheet, including its boundary layers that are characterized by high-speed ion streams, vary greatly within the range of 10 to 1000 km/sec (Frank and Ackerson, 1979). Components of the bulk velocity are often of similar magnitude along the Earth-Sun line (X) and cross-magnetotail (Y) directions. A gross average of a large number of plasma flow observations yields an earthward component of ~ 10 km/sec. At close distances to the Earth the plasmas in the plasma sheet are adiabatically heated by earthward convection and increasing magnetic fields to form the terrestrial ring current (Frank, 1967, 1971b).

Direct detection of the currents associated with the current sheet supporting the magnetotail is difficult due to the small ion and electron drift speeds relative to the thermal velocities. Such recent measurements show that the ion and electron motions in the vicinity of the neutral sheet are nonadiabatic. This situation produces currents from the ion and electron drifts that are additive and in the correct sense for the current sheet of the magnetotail (Frank et al., 1983). Magnetic fields and the electric fields perpendicular to these magnetic fields are weak and < 5 nT and < 0.5 mV/m, respectively. The ion and electron drift speeds are in the ranges of ~ 100 to 200 km/sec and ~ 500 to 800 km/sec, respectively. These drifts yield a current density ~ 1 to $2 \times 10^{-8} \text{ A/m}^2$ in a sheet with thickness ~ 1 to $3 R_E$, which is directed generally from dawn to dusk across the magnetotail. Since the motion of ions and electrons is nonadiabatic and thus energy-dependent (cf. Lyons and Speiser, 1982) self-consistent models of the magnetotail current sheet are expected to be realistic only if these motions are computed in detail. Such a well-founded model of the magnetotail current sheet is not available in the literature and is most appropriately yielded by numerical simulation techniques.

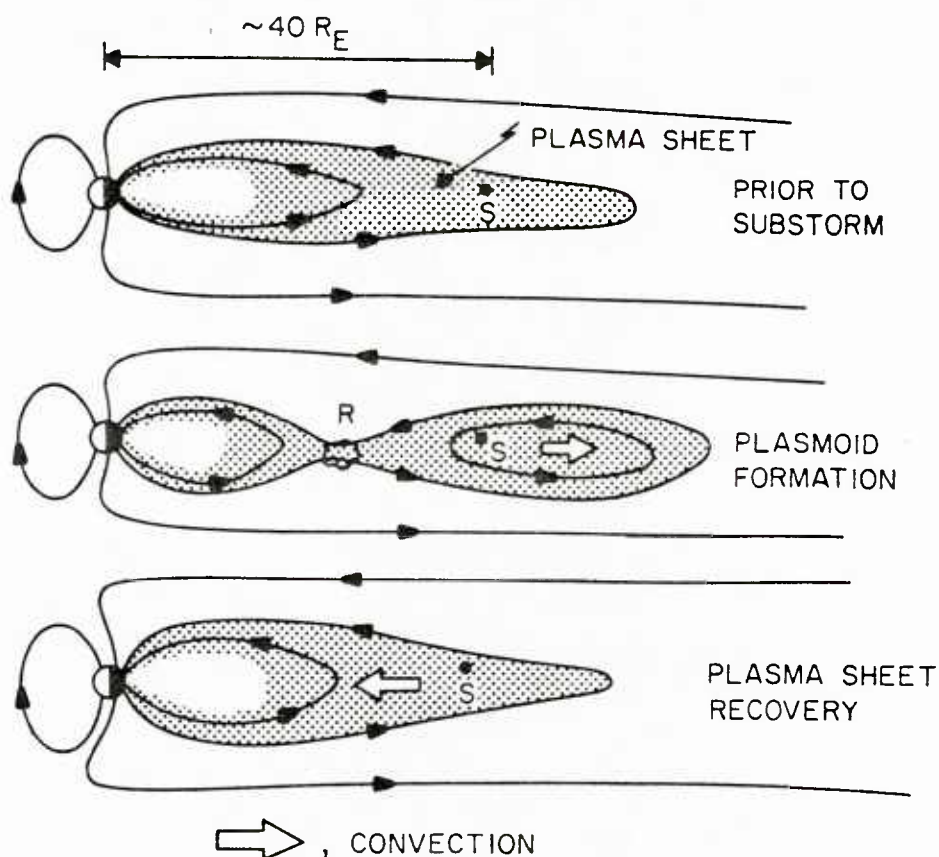


Figure 2. Plasmoid model for magnetotail substorms.

The dynamical behavior of the plasma sheet during magnetic substorms receives the greatest attention of all magnetotail research topics (Hones, 1979, 1984; Hones et al., 1973; Nishida and Hones, 1974; Russell and McPherron, 1973; Nishida and Russell, 1978). The motivation for this intensive investigation arises from the observed dramatic variations of plasmas in the magnetotail during these magnetotail substorms and their close association with auroral substorms in the ionosphere (Akasofu, 1977). The plasma sheet is observed to thin during substorms. Estimates of the rate of this plasma sheet thinning normal to the magnetotail current sheet are ~ 50 to 100 km/sec (Parks et al., 1979). Sometimes during substorms a strong correlation of the magnetic field component perpendicular to the neutral sheet (Z) and the direction of ion flow is found (Hones, 1979). Initially during the substorm antisolar flow and southward magnetic fields are observed. During the substorm recovery earthward flows with northward magnetic fields are present. This correlation is used to deduce that a plasmoid is formed in the plasma sheet during magnetic substorms. The corresponding relationship of the plasmoid relative to the spacecraft position S is sketched in Figure 2. The evolution of the magnetic field topology to a more dipolar geometry at the onset of a substorm

and the return to an extended tail configuration with the recovery is discussed by Fairfield (1973). The earthward jetting of plasmas during substorm recovery as seen at the spacecraft position is interpreted in this model as indicative of the motion of the entire plasma sheet.

The magnetotail is a topologically complex and dimensionally immense region to deduce its behavior and geometry from single-point observations. For example, is the earthward motion of plasmas during substorm recovery the signature of earthward convective motion of the entire plasma sheet or of the passage of a more spatially limited zone of streaming plasmas past the spacecraft position? This observational dilemma is resolved with measurements with two spacecraft (DeCoster and Frank, 1979). There is a boundary layer of generally field-aligned ions on the surface of the plasma sheet. The ion bulk speeds in this boundary range from ~ 100 to 1500 km/sec and are directed earthward. In contrast the ion bulk speeds in the plasma sheet are \sim tens of km/sec. The densities in this plasma sheet boundary layer are ~ 0.1 to 1 cm $^{-3}$. The ranges of ion and electron temperatures are typically 5×10^6 to 5×10^7 °K and 2×10^6 to 2×10^7 °K, respectively, and similar to those observed within the plasma sheet (cf. Frank et al., 1981). The thickness of this boundary is usually 0.5 to $2 R_E$. This plasma sheet boundary layer is a durable feature of the plasma sheet during a wide range of magnetic activity (Lui et al., 1983; Eastman et al., 1984). Thus the downstream acceleration region associated with these plasma flows must be continually active.

Field-aligned currents are observed in the boundary layer of the plasma sheet (Frank et al., 1981). The magnitudes of these field-aligned currents are considerably greater than upper limits for such currents within the plasma sheet proper. The electron temperatures are as noted above and the electron drift speeds, V_D , are in the range of 200 to 1000 km/sec, and thus considerably less than the characteristic thermal velocity, V_T . The current densities are $\sim 10^{-8}$ A/m 2 . Several such sheets can exist in the boundary layer with oppositely directed current densities, i.e., into and out of the ionosphere. The thicknesses of these current sheets are ~ 0.1 to $1 R_E$. These current sheets are mapped into the Region 1 current system over the auroral ionosphere (Potemra, 1979). The ion and electron velocity distributions thus differ significantly from those slowly convecting, quasi-isotropic distributions of the plasma sheet. The character of these velocity distributions is sketched in Figure 3. The electron velocity distributions are characterized by a thermal isotropy $T_{\parallel}/T_{\perp} \sim 1.5$ with the exception of the superposition of lower energy electrons from the ionosphere to give currents directed into the ionosphere (dashed line, northern flux tube). The ion velocity distribution is greatly distorted from that of a convecting Maxwellian (DeCoster and Frank, 1979). This deformation cannot be accounted for by an adiabatic deformation of an initially Maxwellian velocity distribution. On the other hand, the isodensity contours can be generally accounted for by a field-aligned electrostatic potential (DeCoster and Frank, 1979) or perhaps by nonadiabatic acceleration near the neutral sheet (Lyons and Speiser, 1982). It is noted here that the plasma sheet boundary layer

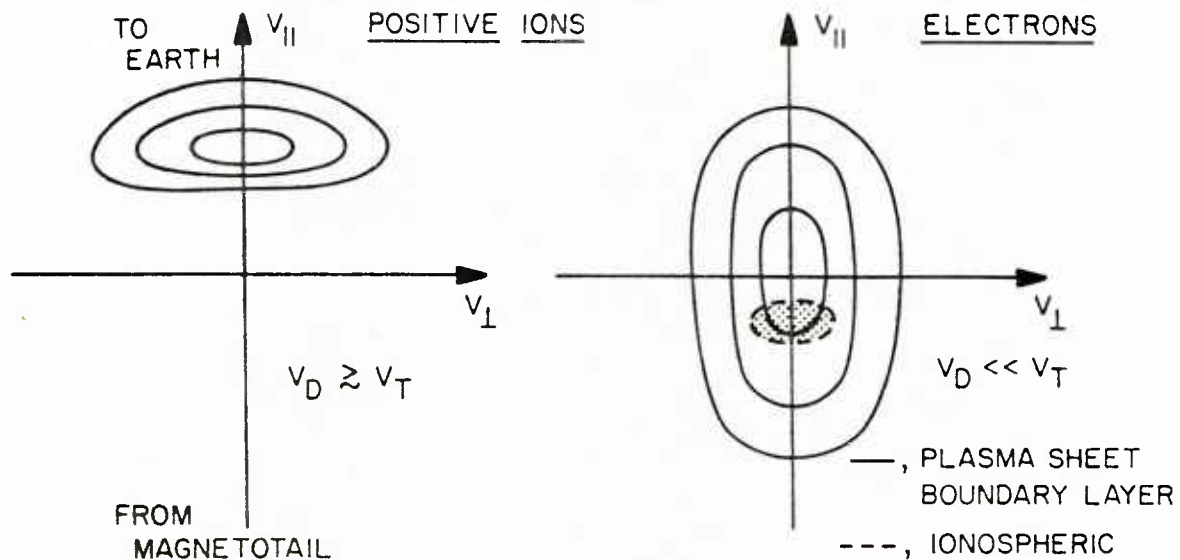


Figure 3. Ion and electron velocity distributions in the plasma sheet boundary layer.

is associated with the discrete auroral emissions in the poleward sector of the auroral oval whereas the equatorward diffuse emissions are identified with the plasma sheet and its extension into the inner magnetosphere as the ring current. Examination of the velocity distributions of ions and electrons in Figure 3 shows that a charge separation earthward along the magnetic field lines will result from the increasing magnetic field. The electric fields arising from the charge separation are presumably modified by the presence of ionospheric plasmas. The complex coupling between these boundary layer and ionospheric plasmas is expected to be usefully studied with numerical simulation. Field-aligned acceleration of electrons at a discontinuity of the convection electric fields is reported for one finding in the plasma sheet boundary layer at $\sim 10 R_E$ (Huang et al., 1984). At low altitudes, ~ 1000 km, such acceleration is seen frequently (Frank and Ackerson, 1972; Evans, 1974; Reiff, 1983). Recently field-aligned electron acceleration is observed in regions extending to altitudes $\sim 3.5 R_E$ over the ionosphere (Lin et al., 1985). Values of plasma parameters given above provide the high-altitude boundary conditions for modeling this as yet unresolved acceleration mechanism; of course, the low-altitude boundary is the ionosphere.

The detection of ionospheric thermal electrons in the magnetotail is rendered difficult by the effects of spacecraft charging and the presence of large fluxes of photoelectrons and secondary electrons. Sojka and coworkers (1985) report several measurements of cold electrons in the vicinity of the plasma sheet boundary layer. The cold ionospheric electron densities are ~ 0.1 to 1 cm^{-3} with a temperature $\sim 10^4$ to 5×10^4 °K. Observations of cold electrons in the magnetotail

deserve further such efforts in order to establish or discount their roles in various possible plasma instabilities in the magnetotail.

Broadband electrostatic noise is present in the boundary layer of the plasma sheet (Gurnett et al., 1976). This electrostatic noise is also observed along these field lines to low altitudes over the discrete aurora (Gurnett and Frank, 1977). On the other hand, these plasma waves are relatively absent in the plasma sheet, including the current sheet centered on the neutral sheet (Anderson, 1983). Various mechanisms are proposed to account for the presence of broadband electrostatic noise (Huba et al., 1978; Grabbe and Eastman, 1984), none of which are completely successful. Since similar broadband electrostatic noise is observed at lower altitudes in the absence of high-speed ion beams, an electron-current driven mechanism may be most likely. The present observations of ion and electron velocity distributions, along with the wave spectral power densities, offer a well-defined challenge for the technique of numerical simulation.

Measurements of the ion composition of the plasma sheet and its boundary layer reveal that both the ionosphere and the solar wind contribute importantly (Shelley et al., 1982; Sharp et al., 1981; Peterson et al., 1981; Eastman et al., 1984). The primary ions used for tracers of the source are O^+ for the ionosphere and He^{++} for the solar wind. Protons are abundant from both sources and are usually the dominant ion in these regions. A variable, large fraction, 0.1 to 0.5, of the hot plasma in the plasma sheet is of ionospheric origin. Thus ionospheric plasmas are present in the magnetotail acceleration region. These ionospheric ions arrive at the downstream acceleration region as field-aligned beams from the ionosphere, that are propagating along magnetic field lines in the region including the plasma sheet boundary layer and extending into the magnetotail lobe and into the adjacent regions of the plasma sheet. These ion distributions are generally field-aligned and flowing in the antisolar direction with speeds in the range of 50 to 200 km/sec. The dominant ions are usually H^+ and O^+ . The ion temperature is $\sim 10^5$ to 10^6 °K. Densities are ~ 0.5 to 5 cm^{-3} . The velocity distributions of these ions exhibit the effects of substantial heating perpendicular to the magnetic field at lower altitudes (Frank et al., 1977). Further the different ion species are often, but not always characterized by the same bulk flow speed parallel to the magnetic field. The mechanism for imparting this bulk motion to these ionospheric plasmas is yet to be identified and remains as an important theoretical goal, along with the wave-particle interaction for the ion heating noted above. Note that a field-aligned potential will provide parallel drifts with the same energy per unit charge for each species. Definitive measurements of the electron temperatures are often difficult within the ionospheric ion beams because the velocity distributions are obscured by those of higher temperature electrons associated directly with the plasma sheet boundary layer; otherwise the electron temperatures are $\sim 5 \times 10^5$ to 2×10^6 °K. The composition of the earthward, or return ion beams in the plasma sheet boundary layer shows that both ionospheric ions and ions within the magnetopause boundary layer are mixed and heated in the downstream acceleration region (Eastman et al., 1984).

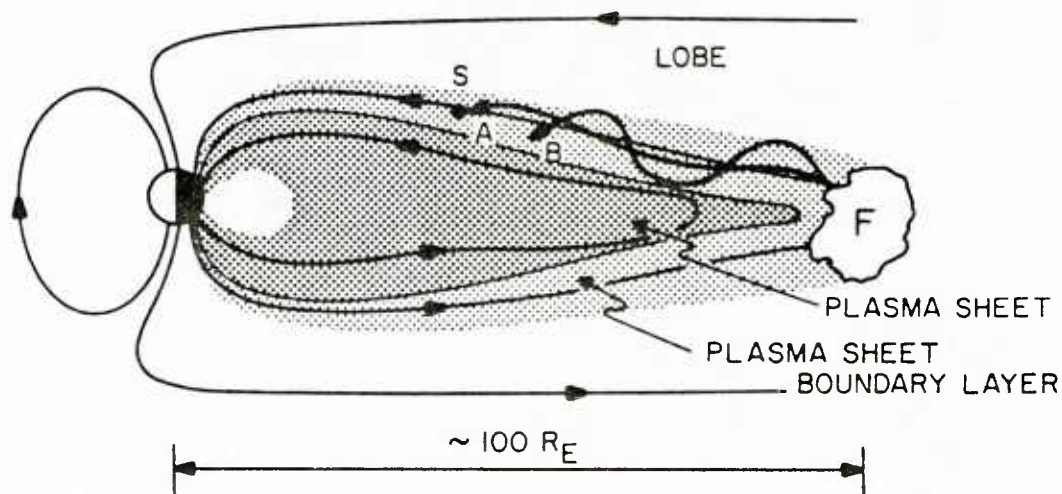


Figure 4. Determination of the location of the magnetotail acceleration region via time-of-flight of energetic ions.

Even though the plasmas within the Earth's magnetotail are characterized by thermal energies in the range of 1 keV to 10 keV, there is firm observational evidence that energetic ions and electrons are efficiently accelerated to energies exceeding 1 MeV (Sarris et al., 1978; Krimigis and Sarris, 1980; Ipavich and Scholer, 1983; Williams et al., 1985). Within the plasma sheet the velocity distribution of energetic ions is the continuous extension of the thermal velocity distribution as a high energy tail beginning at several thermal energies. Examples of such singular ion velocity distribution over the energy range 100 eV to 3 MeV are given by Sarris et al. (1981). This significant enhancement of higher energy charged particle intensities relative to Maxwellian expectations is noted for many of the plasmas in the magnetotail and environs, including the magnetopause boundary layer and the magnetosheath. On the other hand, field-aligned streaming of high-energy ions and electrons which are not directly identifiable as the higher energy component of a thermal plasma is also frequently observed. Such velocity distributions are commonly found in the vicinity of the plasma sheet boundary layer, magnetopause boundary layer and magnetosheath, but are relatively absent within the plasma sheet. These streaming, energetic charged particles are interpreted in terms of either a selective acceleration mechanism for high energy particles, e.g., an inductive electric field from temporal fluctuations of magnetic fields, or the signature of velocity dispersion from a common acceleration region for plasmas and higher energy particles at a remote position in the magnetotail. Williams (1981) provides an analysis of the temporal and pitch-angle fluctuations of energetic ion intensities in the plasma sheet boundary layer, that determines a

location for the acceleration region. Consider two particles, A and B, with the same energy and propagating from an impulsive acceleration event at location F in Figure 4. The spacecraft position is S. Particle A is injected at a lesser pitch angle than B and hence will arrive at an earlier time at position S. Observation of the temporal evolution of the pitch angle distributions at S allows determination of the downstream distance to F. The position can be confirmed by repeating a similar analysis for particles (ions) with different energy. The results of this important analysis position the acceleration region at distances typically $\sim 100 R_E$ downstream from Earth. Thus magnetic field lines threading the plasma sheet boundary layer extend downstream into a region of energetic charged particle acceleration. In overview it is a remarkable feature that such charged particles can be accelerated to these high energies in the weak magnetic fields, tens of nT, and relatively cool, flowing plasmas with speeds in the range of hundreds of km/sec. The application of an in situ observation of the acceleration region is of conspicuous importance to energetic charged particle acceleration in the plasmas surrounding other astronomical objects as well.

As plasma convects earthward in the plasma sheet under the influence of the cross-tail electric field, the ions and electrons are heated adiabatically in the increasing geomagnetic field. This region lies earthward of the current sheet of nonadiabatic motions discussed above. The earthward extension of the plasma sheet is the terrestrial ring current (Frank, 1971b). As the gradient drift velocities increase the ions and electrons drift westward and eastward, respectively. The earthward edge of the electron spatial distributions exhibits well-defined gradients in temperature and pressure as shown in Figure 5 (Vasyliunas, 1968; Schield and Frank, 1970). The ring current lies principally inside this region. Typical electron 'temperatures' as derived from average kinetic energies and the pressures at the inner and outer edges of the electron boundary are 10^6 °K and 10^{-9} erg/cm³, and 5×10^6 °K and 10^{-8} erg/cm³, respectively. The gross nature of the spatial distributions of ions and electrons can be accounted for in terms of electric and gradient drifts (cf. Kavanagh et al., 1968). During substorm activity, earthward convection of magnetotail plasmas is observed and the electron boundary of the plasma sheet similarly moves toward Earth (Konradi et al., 1975; Moore et al., 1981). The earthward edge of this body of new magnetotail plasma that is injected into the inner magnetosphere is referred to as an injection boundary or front. The speed of this plasma convection is sometimes ~ 100 km/sec or similar to that of motion of the boundaries of the more distant plasma sheet at the onset of substorms. In the simplest consideration the charge separation forced by the gradient drift of ions and electrons produces an electric field (Schield et al., 1969). This electric field should generate field-aligned currents that close in the ionosphere. Relatively large current densities are anticipated at the earthward edge of the electron spatial distributions, and field-aligned ions and electrons are observed in the

vicinity of this region. However, to this date there is not a definitive observation of the three-dimensional ion and electron velocity distributions, and thus of the current densities. The lower latitude current system in the auroral oval, Region 2 (Potemra, 1979) is presumed to be associated at least in part with this near-Earth plasma regime. Since the motions of the ion and electron plasmas due to convection and gradient drifts are complex, and a strong coupling to the ionosphere via field-aligned currents is most likely present, numerical simulation is a particularly strong candidate for yielding a satisfactory interpretation of the observed complex plasma behavior and a prediction for the spatial distribution and strength of the field-aligned current system.

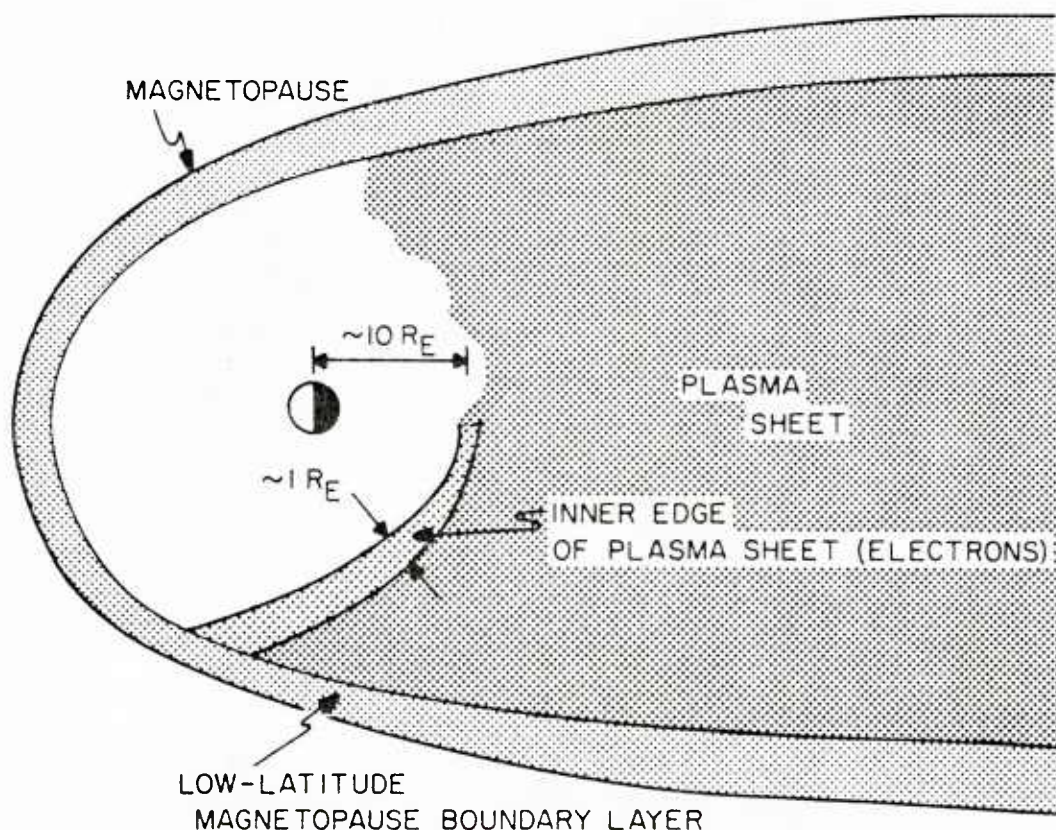


Figure 5. Inner edge of the spatial distribution of plasma sheet electrons.

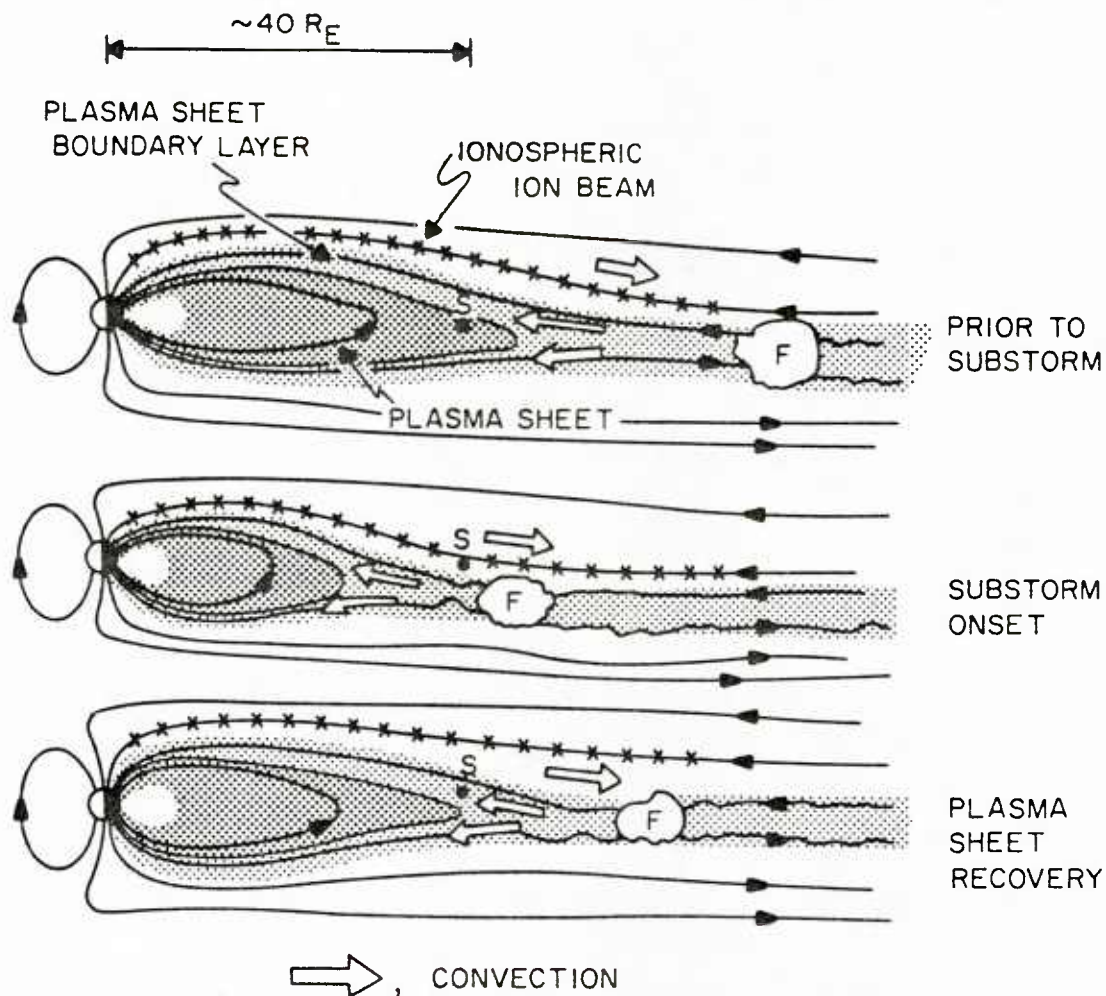


Figure 6. Boundary layer, or fireball (F) model for magnetotail substorms.

An alternative model of the magnetotail is currently being suggested to replace the plasmoid picture that is based on the occasionally observed, striking correlation of the earthward and tailward plasma flows with the sign of the Z-component of the magnetic field during substorms. Recall that the plasmoids are formed by reconnection in the hot plasmas of the plasma sheet and that the plasma sheet boundary layer is not identified as an important dynamical feature in the plasmoid model. The alternative model employs this boundary layer as a primary energy transport region in the magnetotail. Thus it is sometimes referred to as the boundary layer model. The character of ion and electron velocity distributions, the positions of field-aligned currents and ion beams, the location of the magnetotail acceleration region, and the other features of magnetotail plasmas summarized in this writing are accounted for in the boundary layer model. A sketch of this model is shown in Figure 6. A single ion beam from the ionosphere in the magnetotail lobe is shown for simplicity. These ionospheric beams may also be found within the plasma sheet boundary layer and at locations in the plasma sheet just inside this boundary

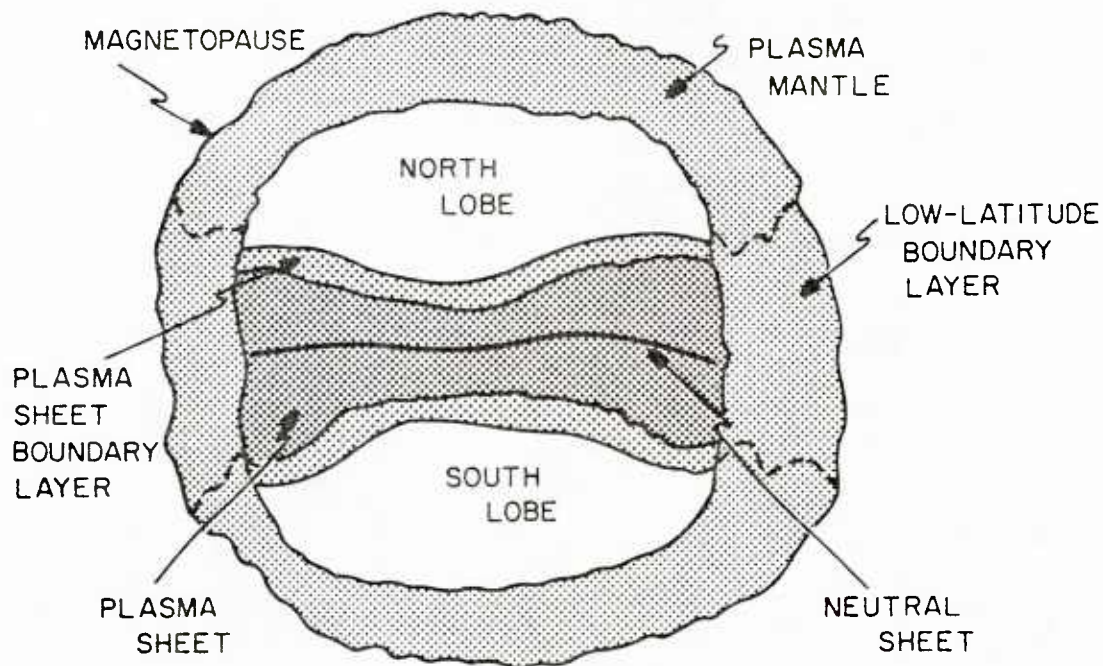
layer. The plasma sheet and its boundary layer are also identified. During relative magnetic quiescence, hot plasmas are convected into the plasma sheet at speeds ~ 10 km/sec. The boundary layer is the principal source of plasmas within the plasma sheet. The expansion of the plasma sheet may also proceed at similar rates. The ionospheric beams, the earthward high-speed ion streams in the boundary layer and the isotropic, slowly convecting plasmas of the plasma sheet are all detected at spacecraft location S during expansions and contractions of the plasma sheet, or of magnetotail flapping motions. The acceleration region F is located at typical distances $\sim 100 R_E$ downstream from Earth and on the boundary of the plasma sheet. This acceleration region is sometimes referred to as a fireball and is not located within the plasma sheet (Frank et al., 1976). Plasmas entering this acceleration region are those of the magnetopause boundary layer and of the ionospheric ion beams.

Acceleration in region F may occur via magnetic reconnection or another mechanism. Magnetic field lines associated with these plasmas are shown to be variously open and closed. The closed magnetic field lines at such distances are sufficiently stretched as to be pinched off by reconnection, if that is the appropriate mechanism. The plasma sheet does not extend beyond the region F, but boundary layers with field-aligned currents and antisunward-directed ion beams are expected to extend considerably tailward. At the onset of a substorm, the plasma sheet is convected rapidly earthward and the acceleration region F follows its outer boundary toward Earth. Thus the plasma sheet thins at the position S. Note that reconnection does not occur in the plasma sheet to form a plasmoid. Currents associated with the acceleration region give large perturbations of the magnetic field near the spacecraft location, at times yielding southward deflections of the magnetic field. As the plasma sheet collapses, ionospheric beams of H^+ and O^+ pass over the spacecraft position. Occasionally these tailward-directed beams are encountered with the above mentioned southward deflection of the magnetic fields associated with the current systems driven by region F.

During the substorm considerable enhancement of tailward plasma flows, tailward-directed intensities of energetic particles, and field-aligned low-energy electrons associated with the magnetotail current system are to be anticipated downstream from region F. During substorm recovery the plasma sheet expands, the magnetic field displays a northward component, and earthward-directed field-aligned ion beams in the plasma sheet boundary layer, as well as occasional tailward ion beams from the ionosphere, are detected. Eventually the plasma sheet expands sufficiently to place the spacecraft S in the hot, slowly convecting plasmas of the plasma sheet. The success of this alternative model, that accounts for many of the observed topological and dynamical features of the magnetotail, stresses the difficulty in interpreting single, or even several-point measurements in terms of unique identifications of the location and details of the acceleration mechanism. A direct encounter with the acceleration region is yet to be convincingly reported. Resolution of many magnetotail issues awaits such an encounter.

6. THE MAGNETOTAIL LOBES

The magnetotail lobes are the two relatively plasma-barren regions in the magnetotail that are bounded at equatorial latitudes by the plasma sheet boundary layers and elsewhere by the magnetopause boundary layers. A cross-section of the magnetotail as seen in a plane perpendicular to the Earth-Sun line and at $40 R_E$ downstream from Earth is shown in Figure 7. These two regions are magnetically mapped into the northern and southern polar regions of the ionosphere, respectively. The plasma densities are $< 0.1 \text{ cm}^{-3}$ and the electron and ion temperatures are estimated to be $< 10^6 \text{ }^\circ\text{K}$ and $< 10^7 \text{ }^\circ\text{K}$, respectively (Bame, 1968). Peterson and coworkers (1984) find typical densities of 10^{-3} to 10^{-2} cm^{-3} with an ion composition comprising H^+ , He^{++} and O^+ . Thus these diffuse plasmas are of both ionospheric and solar wind origins. Their presence in the magnetotail lobes is unaccounted for; however the composition indicates a source related to the plasma sheet and/or its boundary layer. The magnetic flux in the lobes increases with the southward turning of the interplanetary field; thus the total magnetic energy of the magnetotail similarly increases (Fairfield et al., 1981; Makita et al., 1985; Frank et al., 1985). This magnetic energy is released during a substorm. Whether this release of energy is spontaneous or stimulated by a fluctuation of the interplanetary medium is an issue that is unresolved.



MAGNETOTAIL CROSS-SECTION AT $\sim 40 R_E$

Figure 7. Plasma regions in the magnetotail.

The magnetic field lines threading the magnetotail lobes are connected to field lines in the solar wind, i.e., open field lines. This magnetic field topology is supported by the asymmetric access of low-energy electrons, hundreds of eV, to the magnetotail lobes (Yeager and Frank, 1976; Mizera and Fennell, 1978). The asymmetry is such that the lobe with magnetic field directed opposite to that of the interplanetary field is favored. Fairfield and Scudder (1985) show that these low-energy electrons are to be identified with the severely field-aligned electron intensities in the energy range of several hundreds of eV that comprise the high-speed component of the solar wind electron velocity distribution. These electrons are observed to enter into the magnetotail lobe with little or no distortions of their angular distributions, with the exception of that expected from the increasing magnetic field with their motion into the lobe and toward the polar cap. Thus the magnetotail lobes are often, if not always open to the interplanetary medium.

Interest in the magnetotail lobes is currently revived in part due to the findings of tailward-streaming ion beams from the ionosphere (Sharp et al., 1981) and the remarkably active and puzzling behavior of auroras in the polar cap ionosphere during periods of northward interplanetary fields (Burke et al., 1979; Gussenhoven, 1982; Frank et al., 1985). This auroral activity occurs in the polar cap with relatively little fluctuations in intensity and geometry of the auroral oval. The appearance of a transpolar arc across the polar cap to form a theta aurora is currently inspiring several models for the associated topology and global convection system within the magnetotail. The theta aurora is currently believed to be the signature of a torque exerted on the magnetosphere along the Earth-Sun line by asymmetric access of plasmas at the magnetopause, i.e., correlated with the dawn-dusk component of interplanetary magnetic field (cf. Cowley, 1981). Since the plane of the plasma sheet is not observed to rotate significantly in response to the interplanetary field (Hardy et al., 1979b) a 90° reorientation of the plasma sheet cannot account for the transpolar arc. The available diagnostics indicate that the magnetic field lines associated with the transpolar arc are closed whereas the remainder of the polar cap exhibits an open topology (Frank et al., 1985). Ion composition within the transpolar arc plasmas is similar to that of the plasma sheet and its boundary layer (Peterson et al., 1984). Whereas the plasma convection over the polar cap is typically directed antisunward, the convection within the transpolar arc plasmas is sunward. This convection is indicative of a two-cell pattern within the polar cap. Recent examination of in situ measurements within the magnetotail lobes finds the existence of sheets or tubes of plasmas similar to those of the plasma sheet boundary layer (Huang et al., 1985). These plasmas are probably associated with the polar auroras. Thus the magnetotail lobes are no longer to be considered as relatively featureless and passive domains within the magnetotail.

In general, modeling of the energy and mass transport within the Earth's magnetotail, including its lobes, requires in turn a global model for convection electric fields. A realistic description, excluding empirical fits and gross oversimplifications, is most likely achieved by numerical simulation. Even so, this important task is difficult: (1) the outer boundary condition is sensitive to the solar wind, in particular the orientation of the interplanetary field (cf. Cowley, 1982), (2) the inner boundary is the ionosphere, and (3) the electric field configuration and dimensions of the magnetotail acceleration region are unknown. If we are to understand the coupling of the solar wind with the magnetosphere such modeling must be performed. Two of the first severe tests of any model are the more or less permanent presence of a plasma sheet boundary layer and the appearance of a magnetotail convection pattern corresponding to that associated with a theta aurora.

7. THE DISTANT MAGNETOTAIL

Two Pioneer interplanetary spacecraft provide three brief encounters with the Earth's magnetotail at geocentric radial distances of ~ 500 , $1,000$ and $3,100 R_E$. The character of the plasmas differs considerably from the features of the magnetotail inside the lunar orbit (Wolfe et al., 1967; Siscoe et al., 1970; Intriligator et al., 1979). The general appearance of the plasmas in this region is that expected of a wake, i.e., the sporadic presence at the spacecraft of distorted solar wind ion velocity distributions and, at times, large decreases in plasma densities. Such features as the plasma sheet and its boundary layer are not identified. Correlation of these plasma measurements with those of magnetic fields is generally inconclusive as to whether the magnetotail's structure is lobar as nearer the Earth or filamentary (Ness et al., 1967; Walker et al., 1975). The first systematic exploration of the distant magnetotail is provided by ISEE 3 for the radial distance range of ~ 60 to $240 R_E$. These long-awaited observations are briefly summarized here with special attention to their relationship with known features of the magnetotail inside the lunar orbit.

The magnetotail retains its two-lobed structure at the radial distances ~ 60 to $240 R_E$ surveyed with ISEE 3 (Tsurutani et al., 1984b). A persistent region of weaker, variable magnetic fields relative to those of the lobes is easily identifiable with a sheet of plasma at the midplane of the magnetotail (Tsurutani et al., 1984c). The character of these magnetic fields is grossly similar to those found in the plasma sheet and its boundary layer at lesser distances. The strength of the lobe magnetic fields decreases as $\sim R^{-0.53}$ over radial distances R of 20 to $130 R_E$. Beyond $130 R_E$ the lobe magnetic fields are relatively constant, ~ 9 nT (Slavin et al., 1983, 1985). The magnetotail diameter across its midplane between lobes is $\sim 60 R_E$.

in the distant tail and can be compared to a diameter of $\sim 50 R_E$ in the vicinity of the lunar orbit (Howe and Binsack, 1972; Behannon, 1968; Hardy et al., 1979a; Mihalov et al., 1970). Thus a flaring model is appropriate for the magnetotail. Flaring should terminate at the radial distance at which the lobe field reaches its asymptote, i.e., equilibration of lobe magnetic pressure with the hydrostatic pressure of the solar wind (cf. Coroniti and Kennel, 1972). Such a model agrees reasonably with the observed asymptote, $\sim 130 R_E$. The average north-south component of the magnetic field is of considerable interest for identification of a signature of reconnection, or alternatively a large-scale current system differing from that of the cross-tail current sheet maintaining the lobe magnetic fields. Slavin and coworkers (1985) show that there is a region centered in the magnetotail midplane at ~ 100 to $180 R_E$ and $\sim 10 R_E$ in width where the mean magnetic field is directed southward. This region widens to $\sim 30 R_E$ at radial distances ~ 180 to $225 R_E$. At distances ~ 210 to $240 R_E$ the mean magnitude of the southward component is 0.22 nT. The Y-component of the interplanetary field is observed to penetrate the magnetotail lobes and plasma sheet in an asymmetric manner (Tsurutani et al., 1984a; Sibeck et al., 1985). With reference to a cross-section of the magnetotail as divided into north-dawn, south-dawn, etc., quadrants the interplanetary field penetrates more effectively into the north-dawn and south-dusk quadrants when the Y-component is positive. The reverse correlation is also observed. Thus the survey of the magnetotail with ISEE 3 provides an excellent map of the topological evolution of magnetic fields in the magnetotail as a function of radial distance. Only the final intermingling of the magnetotail with the solar wind at greater distances is left unresolved.

The thermal electron plasmas are used to identify various plasma regimes of the magnetotail, e.g., lobes, magnetopause boundary layers, and plasma sheet (Bame et al., 1983). Typical electron densities in the magnetopause boundary layer, i.e., mantle and low-latitude boundary layer, are $\sim 1 \text{ cm}^{-3}$. The temperatures are $\sim 3 \times 10^5$ to 8×10^5 °K with tailward flow velocities ~ 200 km/sec. The densities and temperatures in the lobes are $\sim 0.04 \text{ cm}^{-3}$ and 8×10^5 °K, respectively. Within the region identified as the plasma sheet these plasma parameters are $\sim 0.6 \text{ cm}^{-3}$, 9×10^5 °K and 500 km/sec (tailward). Note that the electron temperatures and bulk speeds are similar in most of these regions. The magnitude of the flow speed in the region identified as the plasma sheet is about an order of magnitude greater than that observed in this region inside the lunar orbit. On the other hand, the flow speed, densities and temperatures are similar to those often observed in the plasma sheet boundary layer at the lesser distances. However these electron bulk velocities are associated with field-aligned currents inside the lunar orbit. Since components of the electron bulk velocity $\vec{V}(V_\perp, V_\parallel)$ are not separated with ISEE-3 measurements, it is not possible to determine whether the observed

electron bulk velocity is associated with a field-aligned current (V_{\parallel}) or convective motion of a magnetic structure (V_{\perp}). Since the electron thermal speeds are large at $\sim 10^6$ °K, $\sim 5,000$ km/sec, relative to expected convection velocities in the plasma sheet, ~ 10 to 100 km/sec, it is not possible to determine the important component V_{\perp} with the electron measurement. Inside the lunar orbit the convective velocity V_{\perp} is determined from ion velocity measurements. No thermal ion measurements are available with ISEE 3 with the exception of ion composition. The plasma sheet in the deep tail exhibits significant densities of H^+ and He^{++} with only traces of the ionospheric ion O^+ (Ogilvie and Coplan, 1984). The composition of the plasma sheet inside the lunar orbit usually includes a large fraction of O^+ . In consideration of these various features of the plasma sheet in the deep magnetotail it is more likely that this plasma regime is to be associated with the plasma sheet boundary layer tailward of the magnetotail acceleration region, not the plasma sheet as identified at distances inside the lunar orbit.

Gosling and his colleagues (1984) identify clearly the presence of the magnetopause boundary layer in the distant magnetotail. The electron density gradients, temperatures and flow speeds are similar to those observed near the Earth in the high-latitude magnetopause boundary layer, or plasma mantle.

Energetic ions in the energy range of several keV to tens of keV are observed in the distant magnetotail and identified as the high-energy tail of the thermal ion distribution in the plasma sheet (Cowley et al., 1984; Gloeckler et al., 1984; Scholer et al., 1984). These ions are flowing generally tailward with speeds ~ 200 to 1000 km/sec. Again the field-aligned and convective components of the flow velocity are not separated. The ion composition is suggestive of a substantial if not dominant contribution from the solar wind. The temperatures of He^{++} are greater than those for H^+ by factors ~ 3 to 4 . The thermal ion temperature is estimated from a straightforward argument for pressure balance to be $\sim 5 \times 10^6$ °K. A survey of the direction of the anisotropy of energetic ions as a function of radial distance finds equal probability of tailward and earthward flows at $\sim 70 R_E$ and dominant tailward flow at $\sim 130 R_E$ and $210 R_E$. This locates the acceleration region at a similar distance from the Earth, $\sim 100 R_E$, as that determined from time-of-flight measurements (Williams, 1981).

Some of the transient fluctuations of electron plasmas, energetic ions and magnetic fields associated with substorms are identified as plasmoids moving tailward across the spacecraft position (Hones et al., 1984; Gloeckler et al., 1984; Slavin et al., 1984). There is little doubt that the plasmas are moving tailward from an acceleration region inside the spacecraft location during these periods. However, there is reasonable doubt as to whether or not

these plasmas convect from the near-Earth plasma sheet at 10 to 30 R_E via the formation of a plasmoid by reconnection at these distances. Observations of the absence of O^+ , the relatively low electron temperatures and the high-speed, field-aligned electron flows more typically found in the plasma sheet boundary layer are several hurdles for this interpretation.

There is plausible evidence of the presence of slow mode shocks associated with reconnection in the distant magnetotail (Feldman et al., 1984; Smith et al., 1984). However the convection electric fields associated with the flow across the shock are not determined, and thus a decisive identification of the shock associated with the merging region is not available. The position of this possible slow-mode shock is located at the boundary between the lobe and plasma sheet. Two essential features to observe are the convection (\vec{V}_\perp) of plasmas in the lobe toward the midplane of the magnetotail and post-shock convection tailward or earthward near the midplane. It is anticipated that future missions are to include direct measurements of electric fields and of the convection velocity \vec{V}_\perp of the thermal ion plasma. For the plasma sheet in the distant magnetotail Scarf and coworkers (1984) find broadband electrostatic noise similar to that observed in the plasma sheet boundary layer inside the lunar orbit. This electrostatic noise is not found in the more dormant plasma sheet at the lesser distances. The ion acoustic anomalous resistivity associated with these broadband electrostatic noise amplitudes in the distant magnetotail is shown to be insufficient to account for the power dissipation expected in the shock (Scarf et al., 1984). However it is possible that sufficient anomalous resistivity is provided by lower hybrid drift waves.

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